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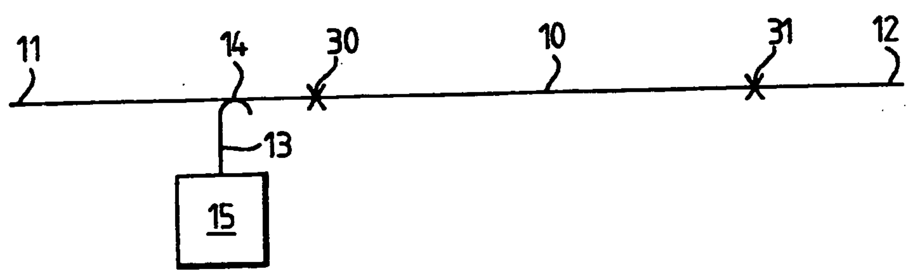
(56) Documents cited
GB 1241724 A GB 1207083 A GB 1138338 A
GB 1015057 A

(58) Field of search
UK CL (Edition K) H1C CA CBAA CBAX CH
INT CL[5] H01S

(54) Er, Nd/Halide glass fibre amplifiers

(57) A fibre amplifier able to operate independently at either or both telecommunications wave bands, 1300-1400nm and 1500-1600nm, eg for frequency division multiplex comprises Nd^{3+} and Er^{3+} which lase independently in halide, preferably fluoride, glass hosts. Pumping at 790-810nm excites both systems. Pumping at 700nm-790nm or 810nm-900nm excites Nd^{3+} selectively whereas pumping at 950nm-1040nm or 1450nm-1540nm selectively excites Er^{3+}. Either or both fibre tails may be used for input and output (cf also Figs 2-5). As an alternative to transmission fibres with SiO_2 cladding and SiO_2/GeO_2 core, tails as well as links to the pump sources may be halide (fluoride) fibre whereby splices (22, 23) are not required. Lasing transitions are detailed (Fig. 6).

Fig. 1.



At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

Fig. 1.

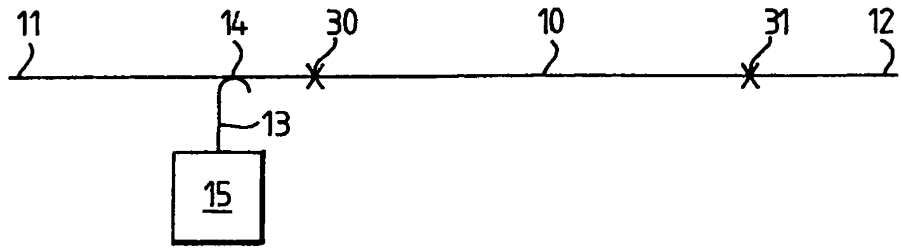


Fig. 2.

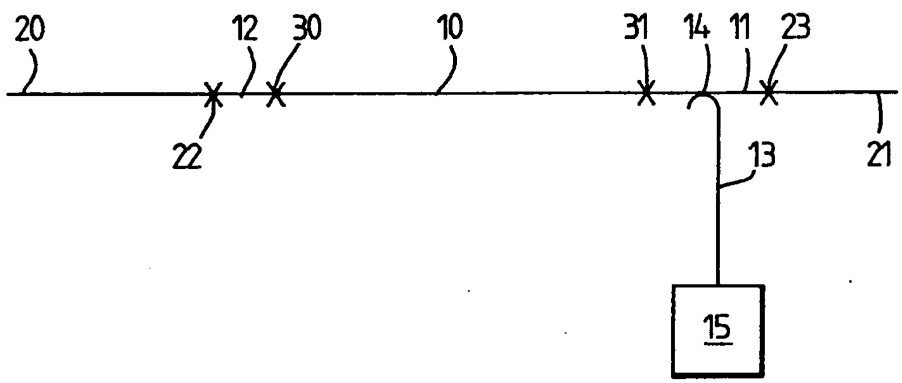


Fig. 3.

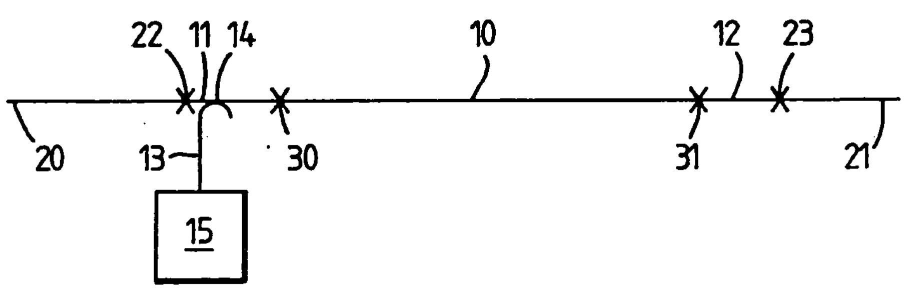


Fig. 4.

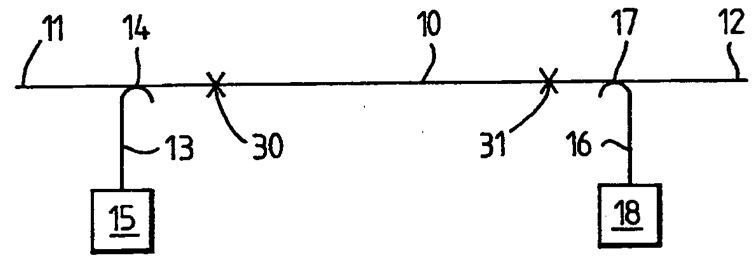

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Fig. 5.

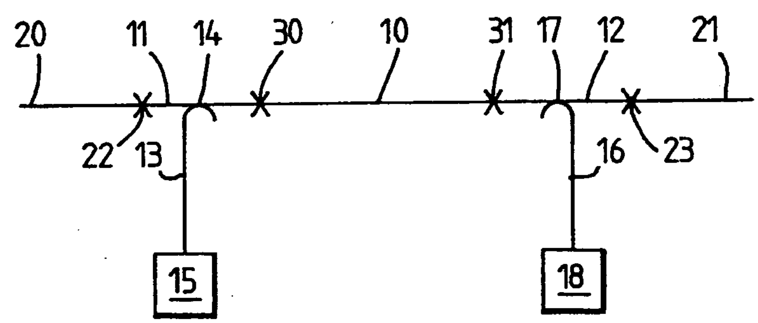
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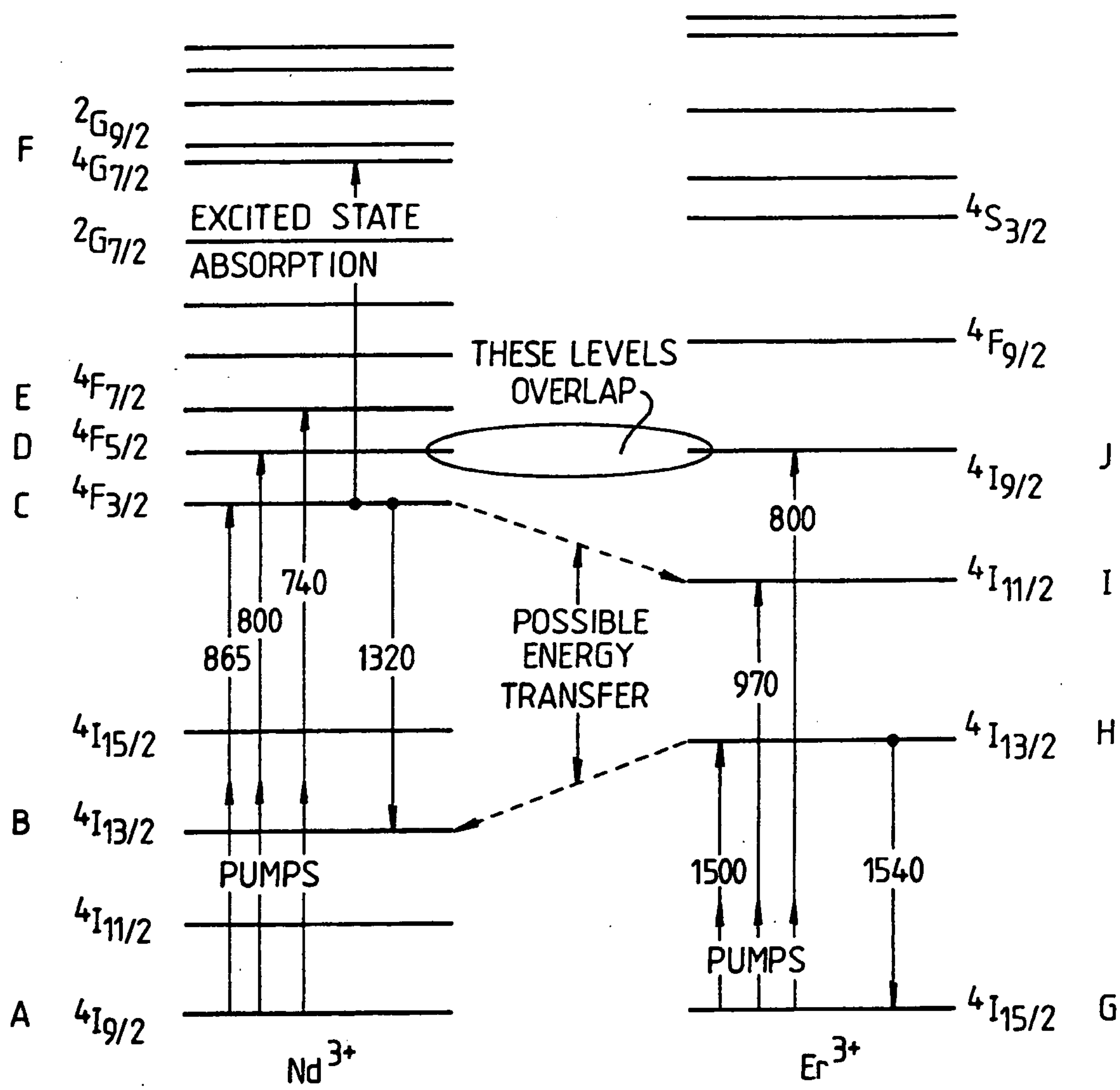
Fig. 6.



$^2G_{9/2}$
F $^4G_{7/2}$
$^2G_{7/2}$
EXCITED STATE ABSORPTION
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D $^4F_{5/2}$
C $^4F_{3/2}$
740
800
865
1320
$^4I_{15/2}$
B $^4I_{13/2}$
PUMPS
$^4I_{11/2}$
A $^4I_{9/2}$
Nd^{3+}
THESE LEVELS OVERLAP
POSSIBLE ENERGY TRANSFER
$^4S_{3/2}$
$^4F_{9/2}$
$^4I_{9/2}$ J
800
$^4I_{11/2}$ I
970
$^4I_{13/2}$ H
1500
1540
PUMPS
$^4I_{15/2}$ G
Er^{3+}

FIBRE AMPLIFIERS

BT PATENT CASE A24113 (PRTY) WP NO: 1116P

This invention relates to fibre amplifiers, eg to fibre amplifiers suitable for use in optical telecommunications systems.

Optical signals can be transmitted over very long distances using glass fibres as the transmission medium. After about 100km the attenuation becomes unacceptable and it is established practice to convert the attenuated signals to electrical form, to amplify or regenerate the electrical signals and to re-transmit in what is effectively an amplified optical signal.

Alternative systems had been proposed in which the attenuated signals are amplified without conversion to electrical form. Specifically it has been proposed to carry out the amplification in a laser amplifier. Specifically this involves providing a region in which atoms (or other species) are excited to produce a population inversion. Photons of the attenuated signal are caused to pass through the excited region whereby their passage stimulates the transition of excited ions to lower energy levels with the production of more signal photons. This process gave rise to the acronym laser, ie light amplification by the stimulated emission of radiation.

Most usages of the term laser imply the co-operation of a resonant feedback system to cause the continuous production of coherent radiation of a narrow wavelength band; such devices are more precisely defined by the term laser oscillator.

In a laser amplifier, feedback would generate noise so the feedback mechanism is absent. It has been proposed to use semiconductor lasers as amplifiers but operable configurations involve interfaces at which unwanted reflections occur and these unwanted reflections cause noise. In fact the adequate suppression of these reflections is very difficult.

Fibre amplifiers have been proposed in which the laser zone is constituted by the core of a suitable optical fibre. The core is doped with a laser species, ie a species capable of undergoing lasing transitions such as a rare earth, eg Nd or Er. The dopant is pumped into an excited state by pump radiation of suitable wavelength which is conveniently provided by a semiconductor device, eg a laser oscillator. The doped fibre is conveniently connected to the pump radiation by fibre couplers and to the transmission fibre by splices. These fibre amplifiers can avoid some of the problems of semiconductor laser amplifiers and their use in transoceanic telecommunications systems was under active consideration in 1989.

We refer to the following publications which relate to fluoride fibres, silica fibres and to the use of Nd and Er as dopants therein.

(1) P W France et al: "Fluoride Glass Optical Fibres", Blackie, 1990, especially Chapters 6 and 10.

(2) S Davey and P W France: Br Telecom Technol J, 7 (1988), 58. This discusses the suitability of Er^{3+}, Nd^{3+} and Tm^{3+} for use in fluoride systems.

(3) Y Kimura and M Nakazawa: "Multiwavelength CW Laser Oscillation in a Nd^{3+} and Er^{3+} Doubly Doped Fiber Laser", Appl Phys Lett, 53, (1988), 1251. This disclosure is limited to silica fibres and it does not describe lasing at 1300nm.

It has however proved difficult to achieve amplification at more than one frequency band, ie in the two wavelength bands of substantial telecommunications interest, ie 1300nm-1400nm and 1500nm-1600nm. This invention relates to fibre amplifiers which have this dual band potential.

The fibre amplifiers according to the invention utilise two lasing dopants, ie Nd for amplification at 1300nm-1400nm and Er for amplification at 1500nm-1600nm, characterised in that said dopants are hosted in a halide, preferably fluoride, glass and that the pump radiation is within the range 700nm to 1600nm.

The invention has two main embodiments.

The first embodiment utilises a pump means in the form of a single light source to excite both of the dopants. The single light source should extend at least over the wavelength band 790 to 810nm and preferably over the band 750 to 850nm. It is doubtful if there are extra benefits in extending the band below 700nm or above 900nm.

The second embodiment uses a pump means comprising two separate light sources, namely a first light source for providing radiation over either a band of 810 to 900nm or over a band of 700 to 790nm, said first light source being adapted to excite the Nd for amplification at wavelenths close to 1340nm and a second light source for providing radiation either over a band of 1450 to 1540nm or a band of 950nm to 1040nm to excite Er for amplification at wavelengths close to 1550nm.

The first embodiment is particularly suitable for use in telecommunications systems operating by frequency division multiplex in both of the above-mentioned bands because the single pump activates both systems. The pump radiation may travel in either the same or the opposite direction as the signal. Duplex operation, in which signals pass in

both directions, is possible. The single pump simplifies the amplifier which is advantageous in small compartments such as a submarine repeater.

The second embodiment provides for separate control over the two systems, eg each of the two light sources may be separately switchable. The second embodiment is clearly more complicated than the first in that it requires duplication of the light sources and their control circuitry. The compensation is that it provides greater flexibility of operation in that if either light source is switched off amplification of the relevant signals ceases. With weak inputs switching off the amplification effectively switches off the equivalent optical channel. Conveniently the light sources are connected at opposite ends of the laser fibre whereby the two wavelengths of pump radiation travel in opposite directions.

To achieve good performance it is desirable to match the properties of the laser fibre to the properties of the fibre in the main system; if it is desired to achieve the optimal performance it would be desirable to make the match as close as possible. In order of importance the matches are:-

(1) <u>Core Refractive Indices</u>

The radiation travels mainly in the cores. If there is too large a refractive index difference between the two cores then a reflective interface could be created. Matching of core indices helps to minimise the risk of reflections.

(2) <u>Core Sizes</u>

Large differences in sizes would tend to create unnecessary difficulty. In most systems the transmission fibre is monomode and, to achieve a satisfactory match, the laser fibre should also be monomode.

(3) Cladding Refractive Indices

The properties of the claddings are less important than those of the cores because the claddings carry less radiation. There is however a better match of fibre properties if the refractive indices of the claddings match.

It is a feature of the host glasses used in this invention that many compositional adjustments are possible whereby the properties of the glass can be controlled to as to achieve the matching mentioned above and also to achieve the refractive index difference to provide guidance in an optical fibre. Furthermore the halide glass of the amplifier is operationally compatible with other glasses used in the main system, eg the SiO_2/GeO_2 blends of conventional telecommunications transmission fibre.

By choosing suitable blends of ingredients both core and cladding indices can be matched. The matching of sizes is a simple mechanical matter.

The halide glasses used as the hosts in this invention are well known compositions. They consist of a plurality of metal halides in solid solution with one another to form a glass phase. Ideally there should be only a single, clear glass phase but in practice a small number of scattering centres are usually tolerated.

The fluoride glasses are a particular sub-set of halide glasses. In these glasses all metal halides are fluorides. As stated above, the fluoride glasses are the preferred hosts for the invention. The fluorides of many metals have been found useful in the formulation of fluoride glasses but we make specific reference to the fluorides of Zr, Ba, La, Al and Na. The acronym "ZBLAN" is often used to indicate glasses based on these fluorides. ZrF_4 usually constitutes at least 45 and

often 50-70 weight % based on the total composition. The BaF_2 is usually about 15 to 30 weight %. LaF_3, AlF_3 and NaF are used in minor proportions to assist in the blending.

The fluorides of other metals, eg Pb and Hf, are sometimes included to improve the glass forming properties of the blends or to adjust the refractive index.

The fibres described above are made by well known processes. For example, appropriate oxides are mixed in the correct proportions, converted into fluorides and melted. Two molten glasses are cast as a preform which is pulled into fibres. As alternative fluorides are mixed so there is no need for conversion before melting. Because the basis of the process is the mixing of the components the proportions are readily varied.

This invention uses Nd ions and Er ions as the lasing species. These elements are most appropriately incorporated as halides into a halide glass, eg NdF_3 and ErF_3 are incorporated into a fluoride glass. The doped glasses are conveniently made as described above. NdF_3 and ErF_3 are available and these compounds are suitable for inclusion in the preparative techniques mentioned above.

It is necessary to provide enough of the lasing dopants to support the required lasing activity. This usually requires at least 1ng of the active species and very few applications would require as much as 1mg of the active species. In most applications 5ng to 2000ng, eg 10ng to 1000ng, of each lasing species would be used. (In this context the lasing species is the rare earth element and amounts of the lasing species should be calculated as the element).

The length of laser fibre is selected to provide the selected amount of the lasing species. For mechanical reasons it would usually be appropriate to select more

than 1cm, preferably more than 10cm, of laser fibre. Similarly, mechanical reasons would usually make it convenient to select less than 100m, preferably less than 10m, of laser fibre. For most applications it is envisaged that 0.5 to 2m of fibre would be chosen. In order to provide a suitable amount of the lasing species, its concentration in the host glass of the core is conveniently 1ppm to 1% by weight, preferably 50-1000ppm by weight.

It should be realised that the host environment, ie the halide glass, exerts a substantial effect upon the performance of the lasing species. The two lasing dopants can, and in most systems do, interfere with one another and/or it is difficult to pump both with a single pump wavelength. We have found that the halide, and especially fluoride glasses, provide an environment in which the two lasing species can operate to provide substantially independent amplification of frequency multiplexed signals in the two bands.

The invention will now be further described by way of example with reference to the accompanying drawings in which:

Figure 1 is a diagram illustrating suitable architecture for a laser amplifier according to a first embodiment of the invention;

Figure 2 shows one way of connecting the amplifier of Figure 1 into a telecommunications system;

Figure 3 shows another way of connecting the amplifier of Figure 1 into a telecommunications system;

Figure 4 is a diagram illustrating suitable architecture for a laser amplifier according to a second embodiment of the invention;

Figure 5 shows the amplifier of Figure 4 in a telecommunications system; and

Figure 6 shows and compares the energy levels in the spectra of Nd^{3+} and Er^{3+}.

The amplifier shown in Figure 1 comprises a length of laser fibre 10 having a cladding of one fluoride glass and a core of a different host fluoride glass doped with both NdF_3 and ErF_3. The laser fibre 10 is connected by a splice 30 to a first silica fibre tail 11 and, at the other end, by a splice 31 to a second silica fibre tail 12. Either of tails 11 or 12 can be used as input; the other is used as output. In a duplex application both are used for both functions. The optical properties of the fluoride fibre 10 should be matched as closely as possible to the properties of the silica fibre tails 11 and 12. The splices are made using an adhesive commercially available for joining fibres. A variety of compositions covering a range of refractive indices are commercially available and selecting a value intermediate the two core values helps to reduce reflections.

The amplifier also comprises a semiconductor (GaAlAs) laser oscillator 15 as a light source providing about 100mW of optical power in the band 780nm to 810nm. The single light source 15 constitutes the pump means in Figure 1. The light source 15 is operationally coupled to a silica link fibre 13 which forms a directionally sensitive optical junction with the tail 11 at 14. This junction passes signals from tail 11 and pump radiation from link 13 into the laser fibre 10. In the case of radiation travelling from laser fibre 10 into tail 11 substantially no signal (ideally none) passes into the link 13.

Figure 2 shows an amplifier according to Figure 1 connected into a telecommunications system. The signals are taken as passing from left to right. Thus the tail 12

serves as input and it is connected by an input weld 22 to an input silica telecommunications fibre 20 whereas the tail 11 serves as output and it is connected by a weld 23 to an output telecommunications silica fibre 21. The pump radiation passes in the opposite direction to the signals. As stated above, the pump radiation covers the band 780 to 810nm and signals in either or both the bands 1300nm to 1400nm and or 1500nm to 1600nm are amplified.

Figure 3 is a modification of Figure 2 in which tail 11 is connected as input and tail 12 as output. This means that the signals and pump radiation pass in the same direction. Both pumping directions are equally effective.

The amplifier can also be used for duplex operation, ie signals traffic passes in both directions at the same time. This gives four signals, ie two directions times two frequencies, which can be amplified independently.

Figure 4 shows a second embodiment whose architecture is a symmetrical version of Figure 1. The pump means takes the form of two light sources 15 and 18 connected to two silica link fibres 13 and 16 which form junctions 14 and 17 with silica tails 11 and 12. Light source 15 is conveniently a semiconductor (GaAlAs) laser oscillator providing light at either 740nm or 865nm to excite Nd^{3+} ions to amplify the band 1300-1400nm. Light source 18 is conveniently a semiconductor (InGa/PAs) laser oscillator to provide light at either 1500nm or 970nm to excite Er^{3+} to amplify the band 1500-1600nm.

Figure 5 shows the amplifier of Figure 4 connected into a telecommunications link. The tails 11 and 12 are connected to input and output silica fibres 20 and 21 at welds 22 and 23. Figure 5 can be regarded as a combination of Figures 2 and 3. Since the device is symmetrical the functions of pumps 15 and 18 can be interchanged.

The system will amplify at either one of 1340nm or 1540nm if only one of the pumps is switched on. It will amplify at both 1340nm and 1540nm if both pumps are switched on simultaneously.

The laser amplifiers specified above give band widths which are particularly suitable for exciting the lasing species. The pump wavelengths quoted above indicate the optimal centre of the band.

In the embodiments illustrated above, the fluoride laser fibre 10 is (adhesive) spliced at 30 and 31 to silica tails 11 and 12. This is particularly suitable when the amplifier is intended for incorporation into a silica telecommunications system because the amplifier can be incorporated by making conventional silica-to-silica fusion splices. The tails 11 and 12 should be the same as the system fibre.

In the above text and in the remainder of this specification the term "silica" fibre denotes fibre based on combined silicon and oxygen, especially fibres having a core or cladding consisting essentially of pure SiO_2 and having a refractive index substantially equal to that of SiO_2. A common form of transmission fibre has a cladding of SiO_2 and a core of SiO_2/GeO_2.

As an alternative, not separately illustrated, the whole amplifier, ie tails 11 and 12 as well as links 13 and 16, is made of halide (fluoride) fibre. In this version the splices 22 and 23 are not required. If incorporated into a silica network it would be necessary to make silica/fluoride splices which is more difficult than silica/silica splices.

The embodiments described above effectively use the ions Nd^{3+} and Er^{3+} as the lasing species and it is important to realise that the energy levels, and hence the

lasing properties, of these species are affected by the host. Therefore the selection of halide glass as the host for the laser, even when the transmission medium is silica, is critical to achieve independent operation at two wavelengths whether one or two pumps are used.

Some theoretical considerations relating to the lasing transitions will now be described with reference to Figure 6 which shows energy levels for the ions Nd^{3+} and Er^{3+} together with their spectral codes. Critical frequencies included in the bands mentioned above are shown in Figure 6 and the associated transitions are also indicated. Two modes will be described.

Mode 1 - using one light source

Pumping close to 800nm lifts Nd^{3+} from its ground state A to level D and it also lifts Er^{3+} from its ground state G to level J; these two levels D and J have almost the same energy. Thus photons near to 800nm excite both species into the population inversion which makes lasing possible. Since it is intended to excite both systems, pump radiation having a relatively wide bandwidth is permissible and it may even be desirable.

After excitation, Nd^{3+} undergoes non-radiative decay to level C and, on stimulation, it falls to level B emitting a photon near to 1320nm (ie the lasing transition). The atom returns from B-A by non-radiative decay.

After excitation, Er^{3+} decays to I and then H followed by lasing near to 1540nm as it returns to its ground state G.

Mode 2 - using two light sources

Using light near to 740nm or 865nm, Nd^{3+} is pumped to level E or level C and similar transition to those described above can follow. These wavelengths have little effect on the Er^{3+}.

Similarly, using light near to 970nm Er^{3+} is pumped to level I followed by non-radiative decay to level H and lasing as described above. Using light near to 1500nm Er^{3+} is pumped to level H which consists of several levels too close to show in Figure 6. This allows the pump to be at a shorter wavelength than the signal.

If it is desired to excite only one system then narrow band excitation would be appropriate, ie wavelengths too close to 800nm should be avoided in both light sources.

Thus, transitions to support the operational modes described above can be found in the energy level diagrams. However, the diagrams also show that the two systems can destructively interfere with one another, eg by transference of energy between the two lasing species. Thus energy could be transferred from Nd^{3+} in level C to Er^{3+} in level I, ie the presence of the Er should inhibit the lasing of the Nd. Similarly Er^{3+} in level H could transfer energy to Nd^{3+} in level B so that Nd should inhibit the performance of Er. We have most surprisingly found that the two systems function substantially independently in the same environment. It should also be noted that the host glass substantially affects lasing performance. For example, it has not been found possible to achieve satisfactory amplification at 1300nm-1400nm using Nd^{3+} as the lasing species in a silica host.

A fibre as specified in Table 1 was used in various tests.

TABLE 1

	CORE	CLADDING
Host Glasses		
ZrF_4 %	53.0	53.0
BaF_2 %	18.5	20.0
LaF_3 %	4.0	4.0
AlF_3 %	3.0	3.0
NaF %	20.0	20.0
PbF_2 %	1.5	NONE
Dopants		
NdF_3 ppm	300	NONE
ErF_3 ppm	600	NONE
Diam (microns)	8	125
RI	1.5030	1.4985

In Table 1 the symbol "%" indicates percent by weight based on the total host glass excluding the dopants. The notation "ppm" is used to define dopant concentrations and it indicates parts per million by weight of dopant based on the host glass.

The fibre was made by mixing the specified fluorides in the proportions stated. The precursors of the core and cladding glasses were mixed in separate crucibles. The ingredients were melted in a furnace and the cladding glass was cast as a tube using a centrifugal technique. The core glass was cast into the bore of the tube to give a preform. The mixing and the first part of the melting were carried out under an atmosphere of pure N_2. The final stages of melting were carried out under a mixture

of pure N_2 and pure O_2. The casting and cooling were carried out under pure N_2. All of these operations were performed in glove boxes to minimise the risk of even slight contamination. When cool, the preforms were removed from the glove boxes and drawn into fibres which were coated with a polymer for mechanical protection. The coating was about 50 microns thick.

Tests were carried out using 1m lengths of this fibre in conjunction with the silica fibre having the features set out in Table 2.

TABLE 2

	CORE	CLADDING
Material	SiO_2/GeO_2	SiO_2
RI	1.463	1.458
Diameter (microns)	8	125

Using the configurations of Figures 2 and 3 with pump 18 at 800nm, signals at 1340 and 1540nm were amplified individually.

Table 3 gives results achieved with the configuration of Figure 5.

TABLE 3

Pumps		Signals	
15	18	1340nm	1540nm
740nm	off	amplified	attenuated
865nm	off	amplified	attenuated
off	1500	unchanged	amplified
740nm	1500	amplified	amplified

The tests defined in Table 3 were repeated using the configuration shown in Figure 6. It was demonstrated that both configurations are equally effective.

CLAIMS

1. An optical amplifier which comprises a laser fibre (10) and pump means (15, 18) operatively coupled to provide pump radiation to said laser fibre, characterised in that the amplifier is operable for the independent amplification of optical signals in the wavelength band 1300-1400nm or in the wavelength band 1500-1600nm or at both said wavelength bands and said laser fibre contains first and second laser dopants contained in a host medium which constitutes their working environment wherein said host medium is a halide glass, said first laser dopant provides Nd as the active species operable to support lasing transitions in the wavelength band 1300-1400nm and said second laser dopant provides Er as the active species operable to support lasing transitions in the wavelength band 1500-1600nm, said lasing transitions occurring independently in said host medium whereby signals in said bands are independently amplified.

2. An optical amplifier according to claim 1, in which the pump means takes the form of a single light source (15) adapted to provide light in a single wave band, said light being adapted to excite both laser dopants.

3. An optical amplifier according to claim 2, in which the light source (15) is a semiconductor laser oscillator.

4. An optical amplifier according to either claim 2 or claim 3, in which the laser fibre (10) is spliced at each end to silica fibre tails (11, 12), one of which is coupled (14) to a silica link fibre (13), which link fibre is operatively coupled to the light source (15).

5. An optical amplifier according to any one of claims 2-4, in which the single light source is adapted to produce energy over at least the wave band 790 to 810nm.

6. An optical amplifier according to claim 5, wherein the single light source is adapted to provide radiation over the band 750 to 850nm.

7. An optical amplifier according to any one of claims 2-6, wherein the light source provides substantially no energy at wavelengths below 700nm or wavelengths above 900nm.

8. An optical amplifier according to claim 1, wherein said pump means comprises first (15) and second (18) light sources, said first light source being adapted to provide light adapted selectivity to excite the first laser dopant and said second light source being adapted to provide light selectivity adapted to excite said second laser dopant.

9. An optical fibre amplifier according to claim 8, in which each of the light sources is a semiconductor laser oscillator.

10. An optical amplifier according to either claim 8 or claim 9, wherein the laser fibre (10) is spliced at one end to a first silica fibre tail (11) and at the other to a second silica fibre tail (12), said amplifier also comprises a first fibre junction (14) at which a first silica link fibre (13) is optically coupled to said first fibre tail, said first fibre tail being coupled to the first light source (15); said amplifier also comprises a second fibre junction (17) at which a second silica link fibre (16) is optically coupled to said second fibre tail, said second fibre tail being coupled to the second light source (18).

11. An optical amplifier according to any one of claims 8, 9 or 10, wherein said first light source is adapted to provide light at either 810nm to 900nm or 700nm to 790nm.
12. An optical amplifier according to any one of claims 8-11, wherein the second light source is adapted to provide light either at 1450nm to 1540nm or at 950nm to 1040nm.
12. An optical amplifier according to any one of the preceding claims, in which the laser fibre is a halide glass fibre.
13. An optical amplifier according to claim 12, in which the halide fibre is a fluoride fibre, the first laser dopant is NdF_3 and the second laser dopant is ErF_3.

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